Clocks and Oscillators in Space

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Abstract

Clocks and oscillators have traditionally played an important role in space navigation and communication, as well as in space science and in tests of fundamental physical laws. Microwave clocks currently in use in space will be replaced by laser cooled clocks capable of significantly improved performance. Beyond this, lasers will play an important role as oscillators used for their spectral purity in interferometry based experiments, and will likely be used as the local oscillators for future optical clocks. In this paper a short review of the role of clocks and oscillators in space is presented, together with some future projections for laser based systems.

INTRODUCTION

Clocks and oscillators have played a pivotal role in enabling space exploration and in providing the capability to perform exacting tests of fundamental physics in space. Traditionally, clocks and oscillators first emerged as the needed instruments for spacecraft communication and navigation functions. Oscillators are a key component of receivers and transmitters on spacecraft and the pervasive use of the Global Positioning Satellite (GPS) system points to the extraordinary capabilities for navigation and position-location achievable with clocks in space. Clocks are also needed for angular position determination of deep-space spacecraft using the techniques of Very Long Baseline Interferometry (VLBI)[1]. The Doppler signature on the received frequency of the signal linking the spacecraft with the Earth receiving station is used to measure the spacecraft velocity relative to earth. The precision with which this key parameter may be measured is related to the clock frequency stability. Furthermore, the required autonomy of future missions translates to the need for high performance space clocks to support their autonomous functions and to enable their communication with Earth.

The role of stable clocks is particularly important for interplanetary and deep space missions, where at the Jupiter distance, for example, an uncertainty of a part in 10^{13} in the clock stability may translate to an uncertainty of a few hundred kilometers in the location of the spacecraft. Similarly, the low spectral purity of the transmitter or receiver oscillator results in corrupted data. This is highly undesirable, especially since to the limitations of the large spacecraft distance and low transmitted power result in a low data rate, which typically ranges from a few tens to a few thousand bits per second.

Clocks and oscillators also play an important, and vastly different, role in connection with scientific investigations of space missions. Since the most precisely determined physical parameter is time, or equivalently frequency or phase, any measurement aimed at testing physical laws to determine the boundaries where they fail, ultimately reduces to a phase, frequency, or time measurement. Consistent with this fact, the frequency stability and spectral purity of the microwave radio links between spacecraft and the ground are exploited extensively to obtain new scientific findings. For example, occultation experiments utilize the spectral purity of the oscillator to yield information regarding the index of refraction and spectral properties of the intervening media through which the radio signals linking the spacecraft to the ground station propagate [2]. The same microwave link between the ground station and the spacecraft acts as an "antenna" for detecting gravitational waves [3]. This unique antenna system responds to a propagating gravitational wave, which imprints a telltale signature with three short components on the Doppler data residuals received on Earth. Two of these are due to the buffeting of the earth and the spacecraft by the traveling wave; the third is a signal originating from the buffeted earth that is reflected back by the spacecraft transponder. This antenna is particularly useful in the search for very long wavelength gravitational waves (as determined by the earth-spacecraft distance) that are outside the sensitivity range of earthbound antennas such as LIGO.

A major test of physics performed by clocks in space is related to a search for the breakdown of general relativity. An important feature of Einstein's field equation is that it contains no free parameters, and any deviation from its predictions would signal a breakdown of the theory. A major prediction of the theory of relativity is the gravitational clock shift, which predicts a shift in the frequency of two clocks located at two points with a gravitational potential difference. On the earth's surface, two clocks separated by a height of a meter exhibit a difference in frequency of a part in 10^{16}. This prediction can be tested by comparing the frequency of clocks that are placed, one on the ground and the other in a spacecraft orbiting the earth. Such an experiment, first performed with a hydrogen maser frequency standard on the Gravity Probe A mission [4], is currently the subject of new investigations armed with more stable and accurate clocks. Two such experiments have been recently selected by NASA for flight onboard the International Space Station (ISS). The first, scheduled to fly in 2004, is the Primary Atomic Reference Clock in Space (PARCS) based on a laser-cooled cesium clock [5]. PARCS is expected to significantly improve on the measurement of the clock redshift performed by Gravity Probe A. The second is the Rubidium Atomic Clock Experiment (RACE), based on a laser-cooled rubidium clock [6]. RACE is expected to fly in 2006, and if combined with a third clock experiment based on a superconducting cavity oscillator (SUMO), will provide a 5000-fold improvement in the test of Local Lorentz Invariance (LLI). An ensemble of clocks including a hydrogen maser and a laser-cooled cesium clock is planned by the European Space Agency, ESA, for another test of the relativistic prediction for the clock shift. This experiment, ACES, is expected to fly in a time window that might overlap with RACE and SUMO. If so, there will be a unique opportunity to compare clocks in flight, and to obtain even higher science returns than planned for each individual clock.

SpaceTime is another mission currently under study that aims to test fundamental physical laws with atomic clocks [7]. This mission is based on comparing the frequency derived from three different atoms in the vicinity of the Sun, where more than 95% of the mass in the solar system resides. The strong gravitational field near the sun allows the highest achievable sensitivity to a possible variation of the fine-structure constant, α, which will manifest itself in a difference in the frequency drift rates of the three atomic species. This experiment is based on a special 'tri-clock" consisting of three ion traps in the same vacuum, thermal, and magnetic-field environment. The traps will hold ions of mercury, ytterbium, and cadmium, each of which is used to realize one of the three clocks. This instrument will fly within four solar radii of the sun, in a spacecraft designed to provide a benign environment despite the intense solar radiation. The journey to the sun will be via a Jupiter flyby, and would take about five years.

THE ROLE OF LASERS ASCLOCKS AND OSCILLATORS IN SPACE

Lasers play an exceedingly important role vis-à-vis clocks in space, both as tools for atomic state preparation and interrogation, and as the local oscillator for optical clocks. The highest performance microwave clocks, such as those mentioned above, derive their superior stability from the interaction of atoms with lasers. Specifically, laser-cooled clocks based on cesium and rubidium already have demonstrated accuracy far beyond the atomic beam standards [8]. Laser-cooled mercury ion clocks have also demonstrated comparable accuracy [9]. It is clear that the application of lasers will continue to improve the performance of microwave clocks, especially those planned for space applications.

Yet another significant role of lasers is in serving as the local oscillator for future optical clocks [10]. The recent demonstration of high stability optical standards, combined with the realization of relatively simple means for optical frequency division [11], signals the advent of optical clocks. Such clocks, based on optical transitions of atoms or ions, will inherently offer much higher performance than microwave clocks. Once developed for space applications, optical clocks with superior performance will enable the highest sensitivity measurements possible with clocks in space.

Beyond the applications sketched above, lasers will be a key element in space experiments that rely on precision metrology. Several missions based on interferometry plan to use spectrally pure and stable lasers for a variety of investigations, ranging from the search for extra-solar planetary systems to the detection of gravitational waves. In the first investigation, Starlight, telescopes separated by 100 m interferometrically combine their detected signals to achieve a sensitivity comparable to a 100 m aperture telescope. The metrology requirement for this mission translates to a measurement precision of 1 pm over the separation distance of 100 m. The corresponding requirement for the laser stability is $5\times10^{-11}\,\tau^{1/2}$, $300\ \mu s < \tau < 20$ ms. This requirement is not difficult to meet on the ground. In space, though, the constraints of mass, power, and reliability make it a challenge to achieve this level of laser stability.

A much higher stability is required for a mission designed to search for gravitational waves [12]. The Laser Interferometer Space Antenna (LISA) consists of three spacecraft separated by a distance of 5×10^6 km. The laser links between the spacecraft is designed to interferometrically detect a relative change in their separation distances produced by a gravitational wave propagating through space and interacting with the three-spacecraft system. To achieve the science goals of LISA for detecting several events per year, caused by a variety of sources such as coalescing binary systems of black holes, a sensitivity to fractional changes of 10^{-23} is required. The corresponding laser stability requirements over measuring intervals of about 1000 s are reduced to 10^{-13} by post-processing the interferometric phase measurements to cancel out laser frequency noise [13]. These schemes, nevertheless, represent added complexity to the design of the spacecraft and its signal processing needs. So lasers with stability exceeding this by two orders of magnitude would significantly simplify the processing task. This level of stability has not been met on the ground, as yet, and will be a significant challenge to implement in space.

The EX-5 mission is expected to place even higher demands on laser stability than LISA. EX-5 is a gravity mapping mission that proposes optical ranging between two satellites separated by about 200 km in polar orbits at an altitude of $\approx$450 km. Nonuniformities in the Earth's mass distribution create anomalies in its gravitational field, which drive variations in the inter-satellite separation. A laser frequency instability of 10^{-13} would simply match the results that could be achieved with microwave ranging, such as in the GRACE mission. To take advantage of the higher sensitivity of optical interferometry, the laser instability must be much less than 10^{-13} for measurement times between $\approx$1 s and the orbit time of $\approx$90 min. The better the short-term stability, the higher the measurement resolution for gravity anomalies as the satellites fly over the earth's surface. The long-term frequency instability at the orbit time limits the accuracy with which the gravity anomalies can be measured.

Beyond the science support, lasers will be significant to operational aspects of the space missions, such as spacecraft communication. Optical communication links can significantly enhance space missions by providing for higher data rates, while reducing the size and the power requirements as compared with microwave systems. Several experiments have already demonstrated space-to-ground optical communications. In these experiments, pulsed lasers and "photon bucket" telescopes comprise one-way communications links. Coherent optical communications might ultimately be required to increase the signal-to-noise ratio and to perform "light experiments" with coherent microwave links analogous to radio science experiments. This means that space-worthy spectrally pure lasers with low input power, mass, and high reliability will be required. The demonstration of this capability may be made in the not-too-distant future.

SUMMARY

In this paper a review of the role of clocks in space was made. The role of clocks in navigation, as well as scientific investigations related to fundamental physics and space science investigations were sketched. Current clocks under development for space are all microwave clocks. The highest performance microwave atomic clocks use lasers to achieve their performance. The use of lasers is expected to expand to support future optical clocks, as well as experiments requiring highly spectrally pure and stable optical sources. Some of these missions, such as LISA, represent a challenge to the clock and laser community to meet their stringent requirements. These and other challenging requirements for high spectral purity and stable laser sources are nevertheless expected to be met with improving laser technology.

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